LLNL-CONF-675913

Optimizing the input and output transmission lines that gate the microchannel plate in a high speed framing camera

J. B. Lugten, C. G. Brown, B. V. Beeman, A. A. Lumbard, F. V. Allen, D. R. Kittle

August 5, 2015

SPIE Optics + Photonics 2015
San Diego, CA, United States
August 9, 2015 through August 13, 2015

Optimizing the input and output transmission lines that gate the microchannel plate in a high speed framing camera

John B. Lugten, Charles G. Brown, Bart V. Beeman, Kenneth W. Piston, Douglas R. Kittle, Fred V. Allen, Alexander A. Lumbard, Jason G. Cruz, Dustin T. Boyle, Dana R. Hargrove, Laura Robin Benedetti, and Perry M. Bell
Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA, USA 94551-0808

ABSTRACT

We present new designs for the launch and receiver boards used in a high speed x-ray framing camera at the National Ignition Facility. The new launch board uses a Klopfenstein taper to match the 50 ohm input impedance to the ~10 ohm microchannel plate. The new receiver board incorporates design changes resulting in an output monitor pulse shape that more accurately reproduces the pulse shape at the input and across the microchannel plate; this is valuable for assessing and monitoring the electrical performance of the assembled framing camera head. The launch and receiver boards maximize power coupling to the microchannel plate, minimize cross talk between channels, and minimize reflections. We discuss some of the design tradeoffs we explored, and present modeling results and measured performance. We also present our methods for dealing with the non-ideal behavior of coupling capacitors and terminating resistors. We compare the performance of these new designs to that of some earlier designs.

Keywords: fast gated microchannel plate, microstrip transmission line, RF impedance matching, Klopfenstein taper

1. INTRODUCTION

Framing cameras used at the National Ignition Facility (NIF) record a time series of 2-dimensional images of an x-ray source, utilizing a microchannel plate (mcp) to amplify the intensity of the x-ray signal. By gating the microchannel plate to amplify for only a short period of time, it acts as a shutter to determine the duration of the x-ray image recorded. A microchannel plate is a thin sheet of leaded glass with a dense array of pores that run through its thickness. An incident x-ray produces a photoelectron near the front side of the mcp (the side nearer the source). When a large electrical potential is present between the front and back surfaces of the mcp, the electron is accelerated toward the back surface. Each electron accelerates some distance down a pore before striking the pore wall and producing a few more secondary electrons. The resulting avalanche of electrons strikes a phosphor, producing light that is recorded on film or a ccd camera. The electrical potential is applied to the mcp by metalized strips on the front surface and a metalized ground plane on the back surface. The amount of charge in the avalanche is very sensitive to the strength of the electric field, E; typically the gain of the mcp is proportional to E^x where $10 < x < 12$. One, two, and four strips of metallization are used on NIF cameras. The framing camera discussed here has four strips, the most commonly used configuration for NIF.

The microchannel plates[1] used in most framing cameras for NIF are typically 0.43 mm thick, and have a closest-packed array of 10 micron diameter pores on a 12 micron centers. This pore geometry gives an open volume of about 63%. The leaded glass has a dielectric constant of about 8, so the volume-averaged dielectric constant for the mcp is about 3.6. The four-strip mcp has four, parallel, metalized strips each 7.5 mm wide. Each strip and its nearby ground plane forms a microstrip transmission line with a characteristic impedance of about 10 ohms. Each strip is driven by a high voltage pulse, typically about -1000 V peak, with about 200 ps duration, FWHM. The typical time required for the electron avalanche to traverse the length of the pore is about 150 ps. Because a strong electric field must be present for the entire travel time of an electron bunch, only photoelectrons produced near the beginning of the electrical pulse have adequate time to propagate along the pore and be recorded. A 200 ps FWHM electrical pulse results in an exposure time of approximately 80 ps FWHM. Ideally the gating pulse has short rise and fall times, resulting in an exposure with a sharp-edged time window.

In a NIF camera, an array of x-ray images is projected onto each of the strips by an array of pinholes. Each strip is driven at one end with the high-voltage pulse that propagates along the strip with a speed of approximately 0.47 c, so the time

*lugten1@llnl.gov; phone 925 432-0567

delay between images on a strip is 7.1 ps/mm of image separation along the strip. For a usable strip length of 31.5 mm, the images on each strip span a time range of 225 ps. The delay between gating pulses for the 4 strips is adjustable.

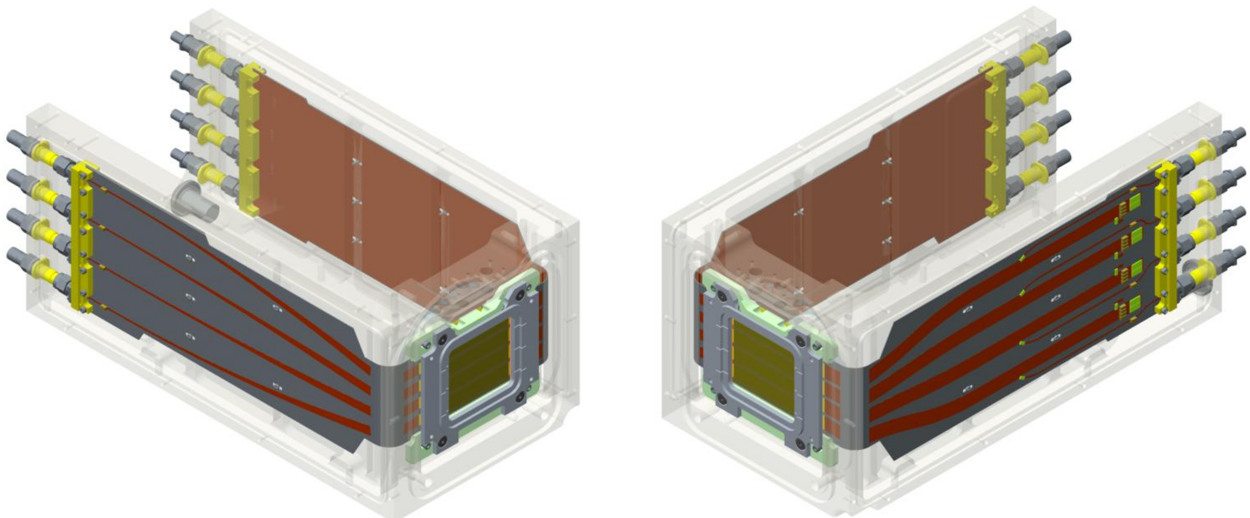


Figure 1. Two views of the 4-strip framing camera head. The left images shows the Klopfenstein taper launch board; input pulses enter at the 4 hermetic feed throughs at the left edge and propagate to the microchannel plate in the front. The right images shows the receiver board, power terminations, and monitor outputs. Although not shown in the images, the four microstrip lines continue around the bend in each circuit board.

The microchannel plate and phosphor are located in the framing camera head, and operate under vacuum. Also in the head and under vacuum are a “launch” board that delivers the gating pulses to the beginning of the mcp microstrips and a “receiver” board that removes the pulses from the ends of the strips. Figure 1 shows a model of the head.

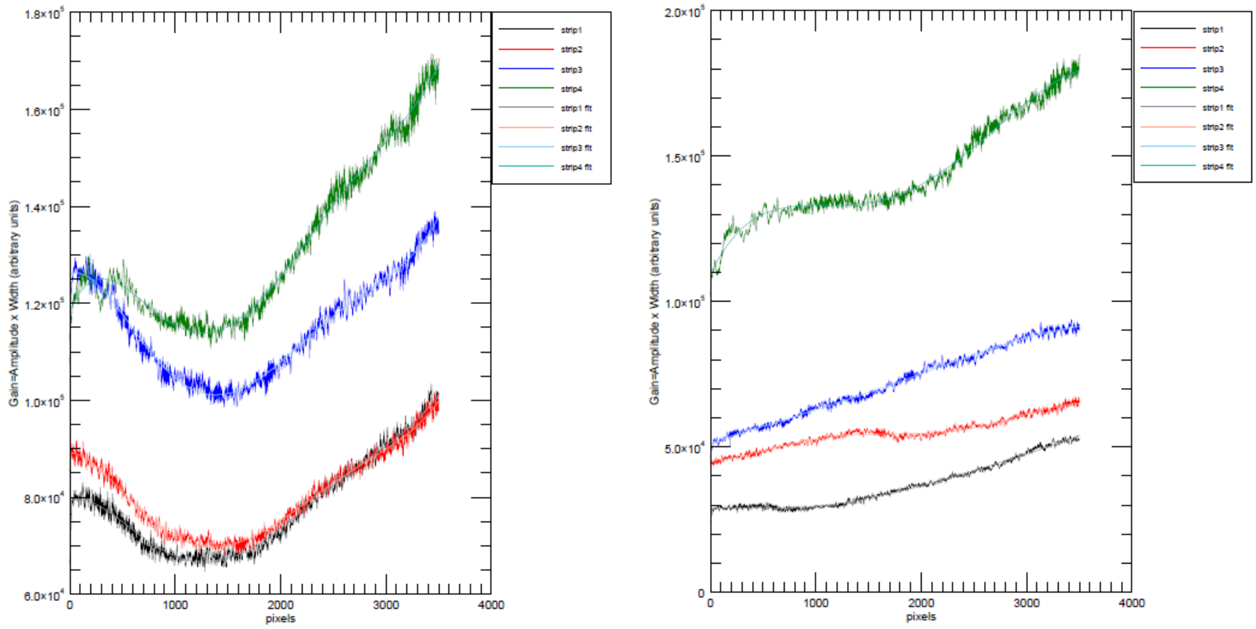
This paper describes some of the design choices for the launch and receiver boards, and some of the challenges to delivering clean, short gating pulses to the mcp. It presents a new launch board that uses a Klopfenstein taper for impedance matching, and a new family of receiver boards with design improvements. We present modeling results, and performance measurements.

2. DESIGN CHOICES, GOALS, AND DIFFICULTIES

The main function of the launch board is to cleanly couple a short pulse that arrives on a 50 ohm coaxial transmission line to a microstrip transmission line that is a good match to the ~10 ohm microstrip transmission line on the mcp. The main function of the receiver board is to cleanly couple the pulse off the mcp, terminate most of the power, and generate a monitor pulse that is a good representation of the pulse that traversed the mcp. For the 4-strip cameras, there are four transmission lines in parallel, each traversing the launch board, the mcp, and the receiver board.

A commonly observed, but undesirable, aspect of framing camera performance is that the gain profile along a strip is substantially changed when the pulse timing on adjacent strips is changed. Figure 2 shows the measured gain profile along the strips of an earlier four strip camera, hGXD-2. The figure is taken from the calibration report[2] for hGXD-2, done by National Security Technologies, LLC. The only difference between the two cases shown is the timing delay between strips. We believe the strong dependence of gain on strip timing results in part from the combination of reflections along individual transmission lines and cross talk between transmission lines. We seek to minimize reflections and crosstalk.

Because of the strong dependence of mcp gain on pulse amplitude, even a small amount of crosstalk between adjacent strips can result in significant gain changes on a strip. The 4-strip microchannel plates have strips that are 7.5 mm wide and are separated by 2.2 mm. We have not changed the geometry of the strips on the mcp, however we have increased the separation between the transmission lines on the new launch and receiver boards. On these boards the lines begin to curve apart immediately as the lines leave the board to mcp interface. Compared to earlier board designs and compared to the mcp, the new boards have significantly larger separation between lines.



a) Gain profiles for co-timed strips

b) Gain profiles for interstrip delays of 200, 400, and 600 ps

Figure 2. Gain profiles along the four strips of framing camera hGXD-2. In panel a) the four strips are co-timed. In panel b) strips 2, 3, and 4 have delays of 200, 400, and 600 ps respectively relative to strip 1. In these images, the gating pulse propagates from right to left.

Reflections on the transmission lines also have detrimental effects. Reflections can result from a sudden change in transmission line impedance, a bend in the line, or the presence of a discrete component on the line. Any single reflection on the receiver board (or from the junction between the mcp and the receiver board) will send a pulse back across the mcp. We fabricate receiver boards with 5 different impedances so we can select the one that best matches a particular mcp. Typically we match receiver board impedance to within +/-2% of the mcp giving a reflection of less than -20 dB at the mcp to receiver board junction. Because the reflected pulse is travelling in the opposite direction as the main pulse, it does not affect the gain profile uniformly along the strip length due to different timing at each point on the strip. On the launch board, two successive reflections produce a small “echo” pulse that trails the main pulse across the mcp; we prefer that the echo pulses produced by any two reflections be less than about -20 dB relative to the main pulse. Sharp bends in microstrip transmission line create reflections; for the new boards we chose to avoid sharp bends in favor of sweeping bends.

Another complication is that because of the high voltage rating needed for discrete components such as coupling capacitors and resistors, they tend to be very large compared to many radio-frequency components; because of their large size they have relatively poor performance at high frequency.

3. LAUNCH BOARD DESIGN AND PERFORMANCE

The pulse that gates the microchannel plate is delivered to the framing camera head through a 50 ohm coaxial cable, and enters the evacuated camera head through a hermetic feedthrough. The launch board couples the 50 ohm input to the approximately 10 ohm mcp, and transitions from a coaxial to a microstrip geometry.

A complete launch board is shown in Figure 3. Seen at the left edge are four end launch SMA connectors that transition from coaxial to microstrip geometry. These are modeled (by license) after designs by Southwest Microwave, Inc[3] and provide very low return loss, typically less than -20 dB. The main difference between our design and the Southwest Microwave design is that four units are ganged together to provide mechanical support for the circuit board. Also visible are the four 2200 pF, 1500 V DC blocking capacitors.

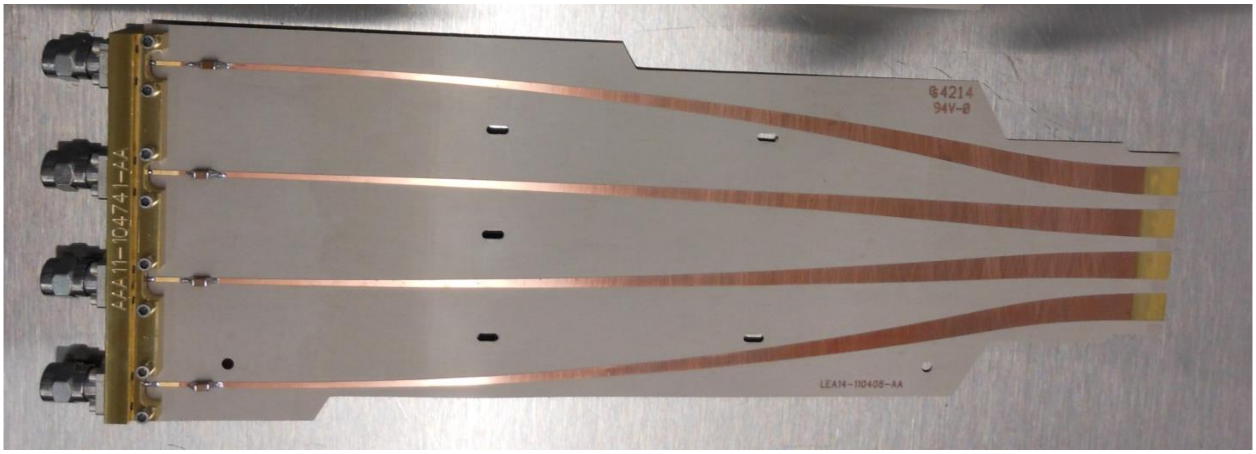


Figure 3. Launch board utilizing a Klopfenstein taper to transition from 50 ohm to 10 ohm characteristic impedance. The 2200 pf DC blocking capacitors are seen near the left edge, and are placed near the 50 ohm to 45.2 ohm impedance jump in the taper.

The launch boards are fabricated from 0.015 inch thick RT/duroid 6002 laminate with 1 oz copper cladding that is manufactured by Rogers Corporation[4]. The dielectric constant for this substrate is 2.94; that is a good match to our needs because a 10 ohm microstrip line is 7.37 mm wide, just slightly narrower than the 7.5 mm wide, 10 ohm (nominal) traces on the mcp

The connection from the launch board (right edge) to the mcp is made by 0.001 inch thick gold foils that are pressed in place by a silicone pad made from Dow Corning 3110 RTV[5]. Foils connect the four microstrip lines on the top and the ground plane on the bottom side. The nominal total thickness of the new boards (substrate plus cladding) is 449 microns. This is an excellent match to the nominal thickness of the mcp which is 431 microns (metallization plus cladding). Earlier launch boards had been made on a 0.020 in thick substrate with 1 oz copper cladding for a nominal total thickness of 576 microns. The improved thickness match to the mcp produces a smaller step in the gold foils that bridge from launch board to mcp.

The tightest bend on the launch board has R/w > 30, where R is the radius of the bend and w is the microstrip width; the four lines begin to bend apart immediately from the mcp interface to minimize cross talk.

3.1. Impedance matching on the launch board

The transition from the 50 ohm impedance of the input feed through to the lower impedance mcp can be handled in several ways. Usually NIF framing cameras have used an “impedance matcher” or “transformer”. In the case of an mcp with 10 ohm strips, one approach is to first couple the 50 ohm input line to two 25 ohm lines that are connected in series. Then after some propagation distance, the two 25 ohm lines are combined in parallel, providing an output impedance of 12.5 ohms. The coupling to a 10 ohm mcp can be very good in principle, giving only a -19 dB reflection, although in practice there are reflections associated with the transmission line bends and junctions.

Some recent NIF cameras, including hGXD-2, have been built with an abrupt impedance jump from 50 ohms to 10 ohms on each line of the launch board. This “mismatch” design has a voltage reflection coefficient of -2/3 at the jump, a –1.76 dB reflection. This mismatch design has three serious drawbacks: higher input voltages are required because 4/9 of the input power is reflected and does not reach the mcp, the pulse source must be able to handle this reflected power, and the shape of the gating pulse is degraded by the large reflection. Compared to matched designs where typically more than 95%, of the input pulse power is coupled to the mcp, the mismatch launch board requires that the input voltage be increased by about 30 to 35%. The pulse voltage at the mcp is about -1000 V peak; the mismatch design requires about -3000 V peak input voltage compared to about -2300 V peak for the matched designs. The high voltage requirements can be challenging given the breakdown limits of components.

Another drawback of the mismatch design is that the pulse shape is noticeably degraded at the mcp compared to the pulse source. This is because the input transmission line from pulse source to mcp has many small, say, -15 to -20 dB reflections that are unavoidable in practice. Sources of reflections include the hermetic feed through, the transition from coaxial to microstrip geometry, and the DC blocking capacitor. The junction between the launch board and the mcp produces significant reflection. Metal foils are used to bridge from the launch board to the mcp on both the microstrip side and the ground plane side. The foils are clamped in place by a silicone pad with dielectric constant ~ 3.2, giving this section of line a lower characteristic impedance than line without the silicone pad. These numerous small reflections combine with the -1.8 dB reflection of the mismatch to produce a train of ~ -20 dB ripples on the trailing edge of the main pulse. Because the gain of the mcp is extremely sensitive to voltage, these ripples significantly change the mcp gain. Crosstalk to adjacent strips (that are gated with user adjustable time delays) is further complicated by the presence of the smaller pulses trailing the main pulse.

3.2. The Klopfenstein taper for impedance matching

For our new launch board, we chose to use a Klopfenstein taper to transition from 50 ohms to 10 ohms. The Klopfenstein (Dolph-Chebychev) taper[6,7] is an excellent choice for this application. It is the optimum taper in the sense that it has the minimum reflection coefficient magnitude in the pass band for a given taper length. We chose a maximum reflection coefficient of -20 dB for the pass band, which along with the 210 mm available length for the taper, results in a pass band consisting of all frequencies higher than 0.39 GHz.

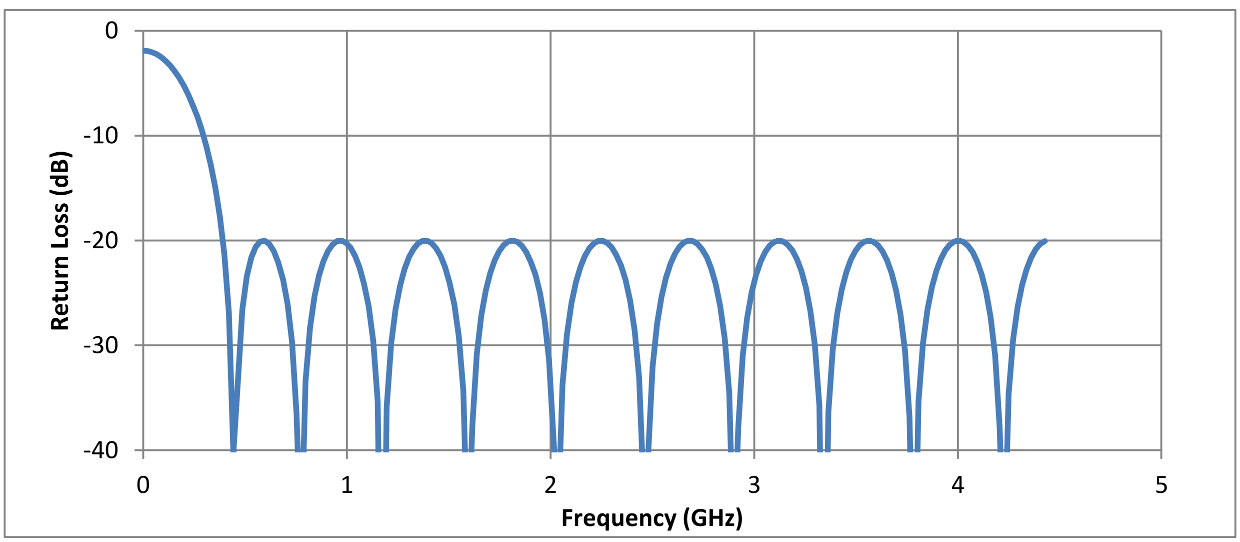


Figure 4. Predicted return loss for 210 mm Klopfenstein taper with -20 dB passband.

We used the design tool at www.microwaves101.com[8] to design the taper. The predicted return loss is shown in Figure 4. To implement the taper in microstrip transmission line, formulas developed by Hammerstad and Jensen[9] were used. For microstrip, the effective dielectric constant varies with impedance, so the length of each section of the taper was adjusted to maintain equal propagation time for each section. To validate the design process, a test launch board was made on a 0.020 in thick substrate having a dielectric constant of 4.50. A single taper on that board was modeled using

CST Microwave Studio[10]. The model results are shown in Figure 5. For most of the 0.4 to 3 GHz band (which contains most of the power in a gaussian pulse of 240 ps duration) the return loss is less than -18 dB. Models that included all four tapers on the board show approximately 2 dB worse return loss.

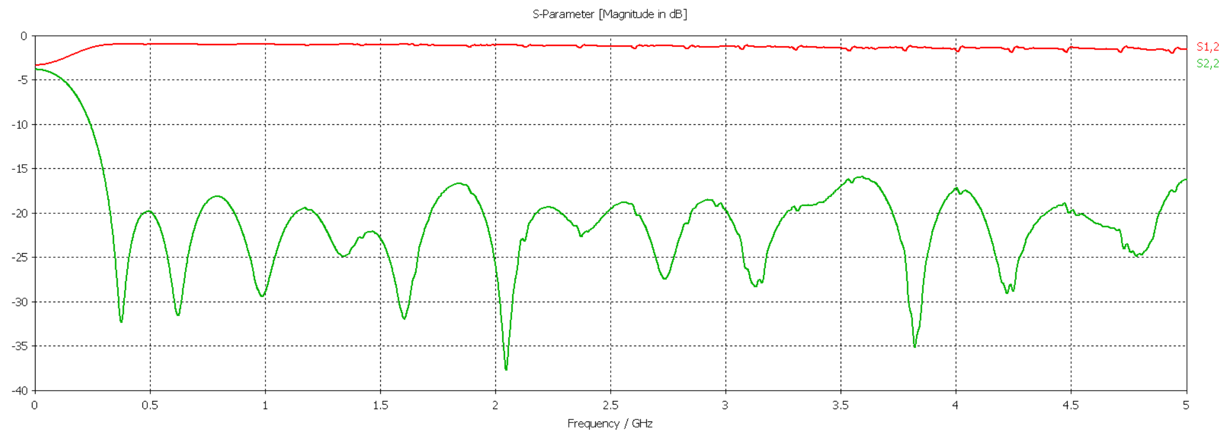


Figure 5. Magnitude of the S-parameters for the Klopfenstein taper from CST model of a single inner line (the other three transmission lines are not included in the model).

The Klopfenstein taper is designed to couple to a 10 ohm mcp, but in practice is used for any mcp between about 9 and 11 ohms. We investigated two different approaches to coupling the taper to an mcp that is not 10 ohms. The Klopfenstein taper has an impedance jump at each end – in our case, from 50 ohms to 45.24 ohms, and from 11.05 ohms to 10 ohms, with the impedance varying smoothly in between. The two approaches we studied were to either jump directly from 11.05 ohms to either 9 or 11 ohms, or to first jump from 11.05 to 10.0 ohms and then jump from 10 ohms to either 9 ohms or 11 ohms. To minimize the reflected pulse, for the 11 ohm mcp, it is slightly preferred to jump directly from 11.05 ohms to the mcp, while for the 9 ohm mcp it is better to jump first to 10 ohms, then to the mcp. We elected to jump from 11.05 ohms directly to the mcp impedance, and to place this jump at the junction between the launch board and the mcp.

3.3. Optimal placement of discrete components and other design details

One advantage of using a taper on the launch board is that the DC blocking capacitors can be placed along the taper at the location where they best match the transmission line impedance. The capacitors we use are 0.060 wide and 0.120 inches long. We find that they best match the taper impedance when placed at the 45 ohm location in the taper.

4. RECEIVER BOARD DESIGN AND PERFORMANCE

The main tasks for the receiver board are to receive the pulse from the mcp with very little reflection, and to generate a monitor pulse that is an accurate representation of the pulse that traversed the mcp. Since a single reflection from the mcp to receiver board junction directs power back across the mcp, the receiver board must be well matched to the mcp. We fabricate a set of 5 receiver boards with 9.2, 9.6, 10.0, 10.4, and 10.8 ohms impedance to mate with the 4 strip mcp; by choosing the best matching receiver board, reflections from the mcp / receiver board junction should be less than -20 dB for any mcp from 9 to 11 ohms. Figure 6 shows a 4-strip receiver board that is optimized to match a 9.2 ohm mcp. The higher impedance receiver boards have narrower traces, larger trace separation, and slightly lower crosstalk between the 4 lines.

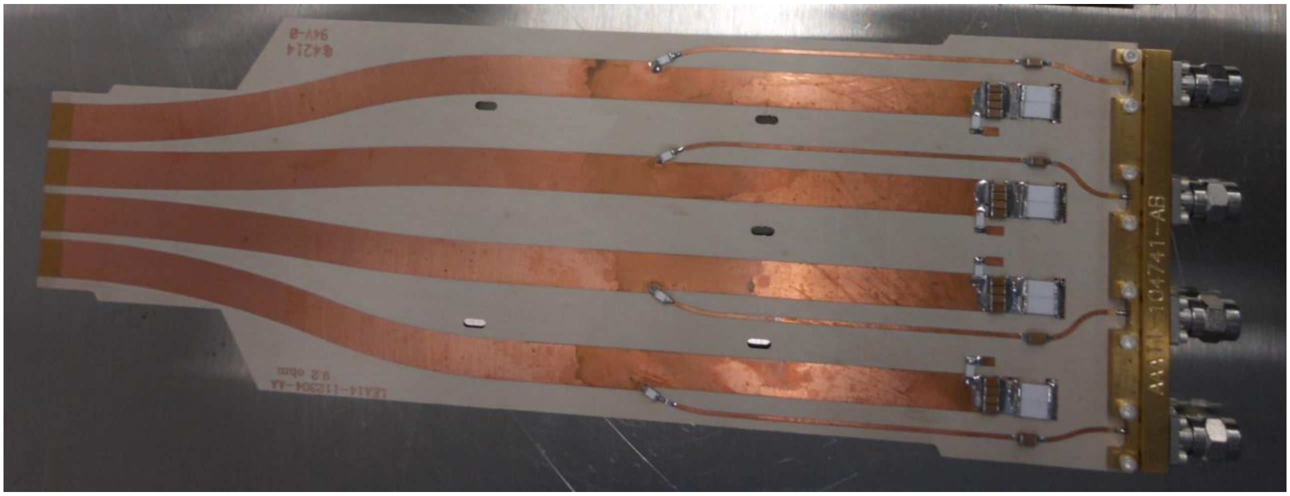


Figure 6. A 9.2 ohm receiver board. The mcp connects at the left edge of the board and the output monitor signals connect to the SMA connectors at the right edge. The 50 ohm monitor signal is picked off from each line by a power divider, seen near the center of the image. Seen at the right are small pads where the DC bias is applied to each line. Also near the right, each line has four DC blocking capacitors in parallel, followed by two parallel power termination resistors connected to ground.

4.1. Creating the output monitor pulse

After a distance of 132.3 mm from the mcp, each transmission line reaches a power divider where it splits into a 50 ohm line that carries the monitor pulse and a second line that carries most of the power. Table 1 summarizes the design impedances of all transmission lines for each of the five varieties of receiver board. The line impedances are such that the power divider has a return loss of less than -20 dB for the input line from the mcp, and for the 50 ohm monitor line. The 44.2 ohm series resistance in the monitor line is necessary to achieve the low return loss, but is also convenient because it reduces the monitor pulse amplitude to about 530 V.

The return loss for the power termination line is about -9.5 dB. Although this match is not as good, little power is incident from this direction. In principle, adding a series resistance to this line at the junction would improve this match. However, any added components would have to be large to handle the high voltage and power; instead we chose to separate the large components from the power divider junction by a significant distance so that reflections from them are delayed in time so they will not degrade the fidelity of the output monitor pulse shape.

Table 1. Characteristic transmission line impedances for the five receiver boards.

Z_{input}	$Z_{power\ termination}$	$R_{monitor}$	$Z_{monitor}$
(ohms)	(ohms)	(ohms)	(ohms)
9.2	10.20	44.2	50
9.6	10.69	44.2	50
10.0	11.19	44.2	50
10.4	11.69	44.2	50
10.8	12.20	44.2	50

The DC blocking capacitors and power terminations are centered at 70 mm from the power divider. At this large separation, the reflection from these components is separated from the main monitor pulse by a delay of about 770 ps. Figure 7 shows a TDT measurement of a launch board / surrogate mcp / receiver board combination. The reflection from the imperfect power termination is seen at the output monitor port lagging the direct response by about 800 ps, as expected. Our earlier designs placed the DC blocks and power terminations very close to the power divider; at this location their reflections distorted the trailing edge of the monitor pulse. Delaying the arrival of the unwanted reflection from the direct signal allows an accurate measurement of the pulse that has traversed the mcp.

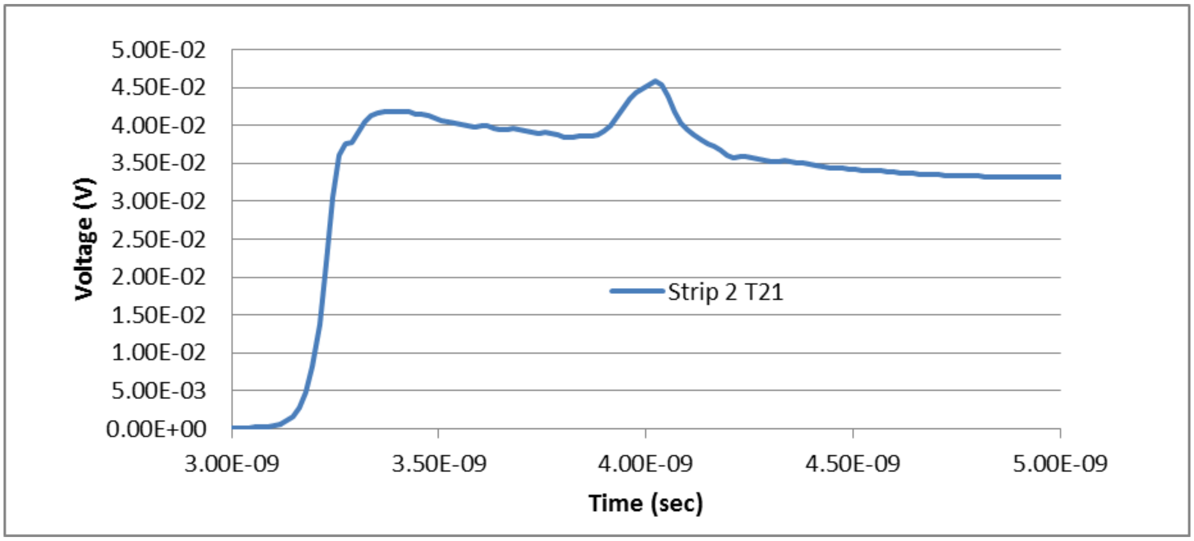


Figure 7. TDT measurement of T21 for strip 2 (an inner strip) for a combined taper launch board + surrogate mcp + 9.6 ohm receiver board. Port 1 is the input to strip 2 on the launch board; port 2 is the monitor output for strip 2. The direct response to the input step arrives at port 2 at 3.23E-9 sec and the reflection from the imperfect power termination at 4.0E-9 sec.

4.2. Termination of the pulse

Almost all of the power in the gating pulse is dissipated on the receiver board, ideally in a well matched load. The peak pulse power is large, approximately $V^2 / R = 1000^2 / 10 = 10^5$ W. However the pulse duration is extremely short so huge termination resistors are not required; we use a pair of 1 W thick film resistors in parallel and find these to be adequate. They are rated for 600 W peak pulse power for pulse duration of 10^{-6} sec. The termination resistors can be matched to transmission line impedance to better than 1% at low frequency, but because of their large package size (0.12 in x 0.25 in) they show significant reflection at high frequency. We find that the reflection is minimized when the resistors are mounted upside down (possibly the conducting metal is closer to the board). There are also significant reflections from the DC blocking capacitors that are immediately upstream of the resistors. For these we use four 2200 pf, 1500 V capacitors in parallel. A model of the receiver board with a resistive film (with cross section identical to the copper microstrip line) placed directly on the board substrate (and no DC blocking capacitors) show that to the arriving pulse the termination first looks inductive, then capacitive. Measurements of the actual board and components show that the termination looks inductive, perhaps in part because the conductive elements of the capacitors and resistors are raised above the substrate.

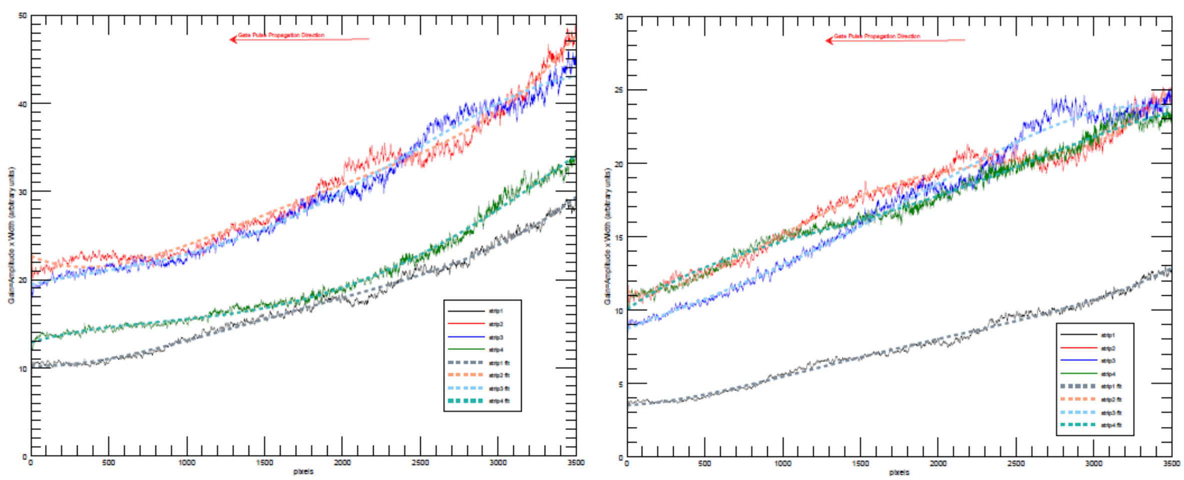
4.3. Other details of the receiver board design

As for the launch board, the total thickness of the substrate plus copper is well matched to the total mcp thickness. Only sweep bends are used on all lines. The 50 ohm monitor lines have bends as sharp as R/w = 7.5; all other bends have R/w > 15. These bends cannot be seen in TDR measurements. Also, like the launch board, the traces are separated soon after the mcp junction to minimize cross talk. The distance from the mcp to monitor pickoff junction is identical for all 4 strips as is the distance from the junction to the power termination. The distance from the junction to the coaxial monitor output is equal to within less than 0.1 mm.

5. CAMERA PERFORMANCE WITH THE NEW BOARDS

The first framing camera assembled using the new Klopfenstein taper launch board and a new 9.2 ohm receiver board is hGXD-6. The gain profiles for two different interstrip timing cases are shown in Figure 8. The figure is taken from the calibration report[11] for hGXD-6, done by National Security Technologies, LLC. The two timing cases shown are identical to the cases shown in Figure 2 for hGXD-2, the previously built four strip camera used as a baseline for comparison. The performance of hGXD-6 is noticeably improved in several important ways compared to hGXD-2.

.



a) Gain profiles for co-timed strips

b) Gain profiles for interstrip delays of 200, 400, and 600 ps

Figure 8. Gain profiles along the four strips of hGXD-6. In panel a) the four strips are co-timed. In panel b) strips 2, 3, and 4 have delays of 200, 400, and 600 ps respectively relative to strip 1. In these images, the gating pulse propagates from right to left.

A major difference in performance is that the camera with the new boards has a similar shaped gain profile for all strips, for the co-timed case and the "heel-to-toe" timing case (200, 400, and 600 ps delays for strips 2, 3, and 4 relative to strip 1). This is quite different from the behavior seen for hGXD-2 for the same two timing cases (Figure 2).

The increase in gain seen at the end of each strip in the hGXD-2 co-timed case helps to minimize the ratio of maximum gain anywhere on any strip to minimum gain anywhere on any strip; for hGXD-2 it is only 2.5:1 compared to 4.6:1 for hGXD-6 for the co-timed case. For the heel-to-toe timing cases, hGXD-2 and hGXD-6 have maximum gain to minimum gain ratios of 6.3:1 and 6.7:1, respectively.

A strong effect, seen for both cameras, is that for heel-to-toe timing, the gain on strip 4 is increased and the gain on strip 1 is decreased, compared to the co-timed case. For heel-to-toe timing, there appears to be a transfer of pulse energy from each strip to the (adjacent) strip that is pulsed next. Thus the gain on strip 1 is decreased (it loses pulse energy to strip 2) and the gain on strip 4 is increased; the gains of strips 2 and 3 change much less (presumably they each receive energy from the preceding strip but lose energy to the following strip). The magnitude of energy transfer from strip 1 to strip 4 in the heel-to-toe timing case relative to the co-timed case is similar for hGXD-2 and hGXD-6.

Crosstalk in faming cameras has been studied thoroughly by Benedetti et al[12]. They made extensive electrical measurements and developed a model that agrees well with the electrical measurements provided that significant cross talk occurs on the launch board for about 200 mm preceding the mcp. That aspect of their model may not be consistent with our observation of strong crosstalk on cameras using the taper launch board or the mismatch launch board; on these launch boards, the lines become much less strongly coupled than the mcp lines after only ~20 mm from the mcp. Their model agrees qualitatively, but under predicts, the observed relative gain (gain / gain of strip 1), which may also suggest stronger cross talk due to the mcp itself.

Finally, the average gate width for hGXD-6 is about 6 ps less than the average gate width for hGXD-2. For co-timed pulses the typical gate width is about 81 ps compared to about 87 ps for hGXD-6 and hGXD-2, respectively; for heel-to-toe timed pulses, the typical gate widths are about 82ps and 89 ps. The shorter gate width is attributed to improved pulse shape delivered by the pulser and pulse forming module (PFM). Figure 9 shows the high voltage PFM output (identical to the launch board input except for losses in the connecting cable) for hGXD-6 and hGXD-2. For hGXD-6, the amplitude of the pulse must be reduced to account for the higher coupling efficiency of the new launch board. The amplitude reduction has allowed a greatly improved pulse shape, with much faster rise and fall times, but still maintaining nearly identical full width at half maximum.

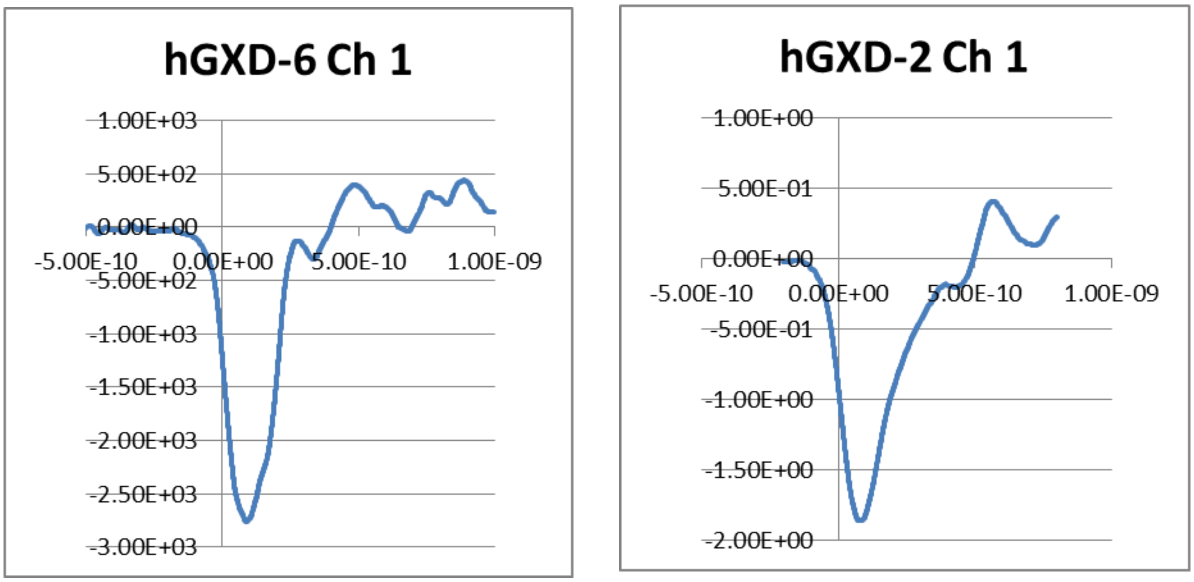


Figure 9. In panel a) the high voltage output from the pulse forming module for strip 1 on hGXD-6. In panel b) the high voltage output from the pulse forming module for strip 1 on hGXD-2. For each camera, the pulses for strips 2, 3, and 4 are very similar to strip 1.

The caveat that should apply to the comparison between hGXD-6 and hGXD-2 is that several things are changed in addition to the boards. The cameras have different microchannel plates, and mcp properties can vary widely. The mcp in hGXD-6 has a small open area ratio (small pores), so the strip impedance is low; we chose the 9.2 ohm receiver board as the best match. Based on a TDR measurement, the mcp in hGXD-6 appears to be unusually lossy, perhaps up to twice as lossy as usual. The other large difference between hGXD-6 and hGXD-2 is the reduced input pulse voltage that has allowed us form a cleaner pulse shape, producing the shorter gate width.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

REFERENCES

[1] Photonis USA Pennsylvania, Inc., www.photonisusa.com

[2] Analysis Report, GXD-F-NOV13, National Security Technologies, LLC, 161 S. Vasco Road, Suite A, Livermore, CA 94551

[3] Southwest Microwave, Microwave Products Division, mpd.southwestmicrowave.com

[4] Rogers Corporation, Advanced Connectivity Solutions, www.rogerscorp.com

[5] Dow Corning 3110 base and Dow Corning F catalyst, www.dowcorning.com

[6] Klopfenstein, R. W., “A Transmission Line Taper of Improved Design,” Proc. IRE, **44**, 1, 31 – 35 (1956).

[7] Kajfez, D., Prewit, J.O., "Correction to A Transmission Line Taper of Improved Design," IEEE Trans, MTT, **21**, 5, 364 - 364 (1973)

[8] Microwaves101.com, www.microwaves101.com/encyclopedias/klopfenstein-taper

[9] Hammerstad, E. and Jensen, O., “Accurate Models for Microstrip Computer-Aided Design”, 1980 IEEE MTT-S International Symposium Digest, (May 1980) Washington D.C. IEEE catalog #80CH1545-3MTT, pp 407 – 409.

[10] CST – Computer Simulation Technology, www.cst.com

[11] Analysis Report, HGXD-partII-006-FEB15, National Security Technologies, LLC, 161 S. Vasco Road, Suite A, Livermore, CA 94551

[12] Benedetti, L.R., Bell, P.M., Bradley, D.K., Brown, C.G., Glenn, S.M., Heeter, R., Holder, J.P., Izumi, N., Khan, S.F., Lacaille, G., Simanovskaia, N., Smalyuk, V.A., and Thomas, R., “Crosstalk in X-ray Framing Cameras: Effect on Voltage, Gain, and Timing,” Rev. Sci. Instruments, **83**, 10E135 (2012)